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Sedimentation Rates in Flow-Restricted and Restored Salt Marshes in Long Island Sound

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ABSTRACT: Many salt marshes in densely populated areas have been subjected to a reduction in tidal flow. In order to assess the impact of tidal flow restriction on marsh sedimentation processes, sediment cores were collected from flow-restricted salt marshes along the Connecticut coast of Long Island Sound. Cores were also collected from unrestricted reference marshes and from a marsh that had been previously restricted but was restored to fuller tidal flushing in the 1970's. High bulk densities and low C and N concentrations were found at depth in the restricted marsh cores, which we attribute to a period of organic matter oxidation, sediment compaction, and marsh surface subsidence upon installation of flow restrictions (between 100 and 200 years before the present, depending on the marsh). Recent sedimentation rates at the restricted marshes (as determined by ^{137}Cs and ^{210}Pb dating) were positive and averaged 78% (^{137}Cs) and 50% (^{210}Pb) of reference marsh sedimentation rates. The accumulation of inorganic sediment was similar at the restricted and reference marshes, perhaps because of the seasonal operation of the tide gates, while organic sediment accretion (and pore space) was significantly lower in the restricted marshes, perhaps because of higher decomposition rates. Sedimentation rates at the restored marsh were significantly higher than at the reference marshes. This marsh has responded to the higher water levels resulting from restoration by a rapid increase in marsh surface elevation.

Introduction

Tidal salt marshes are features of the intertidal zone, implying that in order to survive, marshes must maintain their position relative to water level by accreting sediment at a rate roughly equal to the rate of local relative sea level rise (RSLR; Patrick and DeLaune 1990; Mitsch and Gosselink 1993; Warren and Niering 1993; Kearney et al. 1994; Nydick et al. 1995; Nyman et al. 1995; Reed 1995; Roman et al. 1997). Both inorganic matter (IM) imported on the tides and autochthonous organic matter (OM) from macrophyte production contribute to the accretion of the marsh surface, with the balance between the two varying from marsh to marsh (Stevenson et al. 1988; Bricker-Urso et al. 1989; Nyman et al. 1995). Even in situations where IM inputs dominate the mass accumulation of sediment, OM may play a crucial role in vertical accretion. This is due to the lower particle density of OM, as well as its ability to increase sediment pore space, which generally makes up the majority of sediment volume (Bricker-Urso et al. 1989).

Many researchers have examined the relationship between the rates of sediment accretion and various aspects of the hydrologic regime, particularly two related but distinct hydrologic parameters: (a) tidal range; and (b) frequency of inundation. Looking at the first parameter, Stevenson et al. (1986) found a good correlation between tidal range and net accretion (accretion minus RSLR) for 15 United States marshes, which was attributed to an increased input of mineral sediment in marshes with greater tidal energy. Callaway et al. (1997) found relatively high net accretion rates in several low-tidal-range Gulf Coast marsh systems, substantially worsening Stevenson's correlation. Wood et al. (1989), in studying a set of Maine marshes, found no correlation between accretionary balance and tidal range, possibly because all the marshes studied were on the upper end of the tidal range scale.

With regard to frequency of inundation, several studies have suggested that more frequently inundated marshes have higher IM inputs (Gosselink and Turner 1978; Craft et al. 1988; Craft et al. 1993; Cahoon and Reed 1995), although Hutchinson et al. (1995), using sediment traps, found that temporal patterns in sediment deposition at two South Carolina marshes were not related to duration of inundation; this may be due to the

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short time scale involved in sediment-trap studies (French et al. 1995; Roman et al. 1997). In terms of OM inputs, results are mixed. Cahoon and Reed (1995) found an increase in OM accretion with longer inundation, which they attributed to increased inputs of allochthonous OM. Callaway et al. (1997) found an increase in OM accretion with more frequent inundation (along transects); they suggest that this may be due to higher productivity in the more frequently inundated sites as a result of improved drainage. On the other hand, several studies have found higher OM accumulation in infrequently flooded sites, which may be a result of reduced tidal export of autochthonous OM (Gosselink and Turner 1978; Craft et al. 1988; Craft et al. 1993). Differences in inundation can also be expected to affect OM decomposition rates; wetter sites may experience enhanced decomposition of aboveground litter (Halupa and Howes 1995), but lower or equal rates of belowground decomposition (Hemminga et al. 1988, 1991; Hemminga and Buth 1991; Nyman and DeLaune 1991).

Especially interesting cases in terms of marsh accretion are the flow-restricted marshes that are common in the northeastern United States. The construction of transportation corridors (highways, local roads, railroads) along the coast has resulted in reduced tidal flow into marshes through narrow gaps beneath bridges and through embankments. In addition, dikes have been installed at the mouths of many marshes for the purpose of controlling water levels (Rozsa 1995a). These flow restrictions invariably cause reduced tidal range and a decrease in tidal exchange between the marsh and the estuary. They may also lead to a drastically reduced inundation frequency and substantial lowering of the water table, especially when ditches are also dug in the marsh to improve drainage. Flow restrictions often have significant impacts on the vegetation (Roman et al. 1984; Sinicrope et al. 1990; Orson and Howes 1992; St. Omer 1994), the habitat quality (Montague et al. 1987) and the chemistry (Gosling and Baker 1980; Soukup and Portnoy 1986; Vranken et al. 1990; Portnoy 1991; de Jong et al. 1994; Roman et al. 1995; Anisfeld and Benoit 1997; Portnoy and Giblin 1997b) of the marsh. There has been substantial interest in recent years in restoring degraded salt marshes by increasing tidal flow (Sinicrope et al. 1990; Frenkel and Morlan 1991; Barrett and Niering 1993; Peck et al. 1994; Roman et al. 1995; Rozsa 1995b; Portnoy and Giblin 1997a).

Several studies have examined the effects of flow restrictions on accretion rates. Louisiana marshes that are subject to flow restrictions but remain waterlogged appear to have lower accretion rates than unrestricted marshes (Cahoon and Turner 1989; Reed 1992). In New England, measurements of surface elevations in several diked marshes have shown substantial subsidence (~25–100 cm) compared to unrestricted marshes (United States Army Corps of Engineers 1994a; Roman et al. 1995; Rozsa 1995b; Portnoy and Giblin 1997b), with the effect being much larger for drained than for waterlogged marshes (Portnoy and Giblin 1997b). Portnoy and Giblin (1997b) found lower IM content (relative to an unrestricted marsh) in sediments from a diked waterlogged marsh, presumably because of the reduced flow of sediment-laden tidal water. A diked drained marsh, on the other hand, had higher IM content, presumably because of increased OM decomposition. Two diked Oregon marshes also showed substantial subsidence relative to reference systems (Frenkel and Morlan 1991; Thom 1992). Subsidence has been widely observed in other types of drained wetlands (Hutchinson 1980; Armentano and Menges 1986).

The impacts of flow restrictions on marsh sediments should be divided into acute effects (seen upon installation of flow restrictions) and long-term, chronic effects. We hypothesize the following course of events for diked drained marshes:

1. The sudden drop in water level caused by introduction of flow restrictions leads to subsidence of the marsh surface, as a result of both peat collapse and increased rates of OM oxidation.
2. The period following this initial trauma is one of recovery: the marsh surface, which is now lower in elevation as a result of subsidence, is once again closer to water level, resulting in an increase in inundation relative to the first period. In this period, the accretion rate, though positive, may be lower than in natural marshes both because of the lower tidal range and because of the fact that the marsh surface is still inundated less frequently than in natural systems.
3. If there is an attempt to restore the marsh, the subsequent increase in water level may disrupt the new steady state that has been reached, resulting in either conversion to open water or recovery of marsh surface elevations to higher levels.

In order to examine the effects of flow restrictions on salt marsh accretion processes, we have measured sedimentation rates in cores from 6 Connecticut salt marshes. The salt marshes examined include restricted and reference (control) marshes, as well as a marsh that was recently restored by removal of flow restrictions.

Study Sites

A total of 14 sediment cores were collected from 6 salt marshes located in Branford and Guilford,

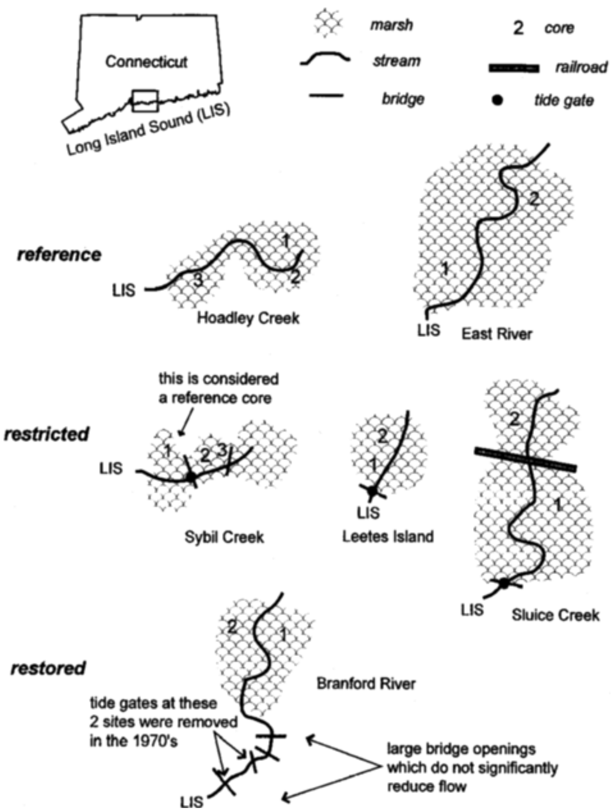

Fig. 1. Map of marshes studied and coring sites.

Connecticut, along the coast of Long Island Sound (Fig. 1 and Table 1). Six of the cores ("restricted") were taken from locations that were subject to anthropogenic flow restriction in the form of tide gates, which are simple flap valves that prevent the incoming tide from flooding the marsh, but open on the ebb tide to allow the marsh to drain. At two of these marshes, the tide gates are operated on a seasonal basis, being opened in the winter to allow a period of normal tidal flushing; salt hay mowing also still takes place at these two marshes. In addition, six cores were collected from unrestricted sites (reference), and two cores were taken from a marsh that was restored in the mid-1970s by removal of flow restrictions (restored). Table 1 summarizes the type of flow restrictions present in the various sites, as well as the hydrologic data available for these marshes from this study and others (United States Army Corps of Engineers 1994a, b). The restricted marshes all show a substantial decrease in tidal range and absolute elevation of high water when compared to the reference and restored marshes. Quantitative data on frequency and duration of inundation are not available, but considerable personal observation suggests that the restricted marshes are inundated much less frequently than the reference marshes during the months when the tide gates are in operation.

Methods

At two of the marshes (Hoadley and Sluice), tidal ranges for selected spring tides (Table 1) were obtained from water level recorders installed in the marshes as part of a detailed study of water chemistry and tidal exchange in these systems (Anisfeld and Benoit 1997). For 3 of the marshes (Branford River, East River, and Sybil), tidal range was measured at various locations over a spring tidal cycle on October 28, 1996 using graduated lines suspended from bridges.

Core sampling apparatus consisted of 12.7-cm diameter PVC pipe, which was pre-sliced into 1–2 cm increments and re-assembled using waterproof tape into a ~40 cm cylinder; this allowed easy division of the core into depth increments following collection. A sharpened steel blade was attached to the bottom of the coring apparatus to facilitate introduction into the peat and to minimize compaction. After insertion into the peat, compaction was estimated by measuring the difference in peat height inside and outside the core; compaction was generally < 5%. Upon return to the laboratory, the PVC cylinder was disassembled (one ring at a time) and sediment sections were removed and dried to constant weight at 105°C. Dry bulk density (BD; g cm^{-3}) was calculated as dry sediment weight divided by the known volume of each sediment section. Bulk density was also calculated in 10-cm depth increments by combining the data from individual sediment sections. Bulk density data were not available for core Sluice-1, so densities for Sluice-2 were substituted where necessary for calculations.

Each dried section was ground using a coffee mill and packed into an aluminum can, which was hermetically sealed, set aside for 30 days (to allow equilibration of ^{214}Pb with ^{226}Ra), and counted for 8–24 h on a Canberra low-background high-purity Ge gamma counter. The areas of the peaks at 44–49 keV (^{210}Pb), 348–354 keV (^{214}Pb), and 654–665 keV (^{137}Cs) were recorded. All counts were corrected for self-absorption by counting point sources on top of each can (Cutshall et al. 1983). The efficiency of the gamma counter was determined by counting cans containing standards of known ^{210}Pb, ^{214}Pb, and ^{137}Cs activity. Excess ^{210}Pb ($^{210}Pb_{xs}$) was determined for each section by subtracting the activity of ^{226}Ra (as measured by the ^{214}Pb peak) from the activity of ^{210}Pb.

Vertical sedimentation rates (cm yr^{-1}), referred to here as accretion rates, were calculated using both ^{137}Cs and ^{210}Pb dating. Average accretion rates over the last ~30 years were derived from assigning the peak in ^{137}Cs activity to the 1963 peak in ^{137}Cs

TABLE 1. Characteristics of marshes studied.

Core Name	Restriction History	Dominant Vegetation	Spring Tidal Range[a]	High-tide Water Elevation (Spring Tides)[b]	Marsh Location (Mouth)
Reference					
Sybil-1	None (upstream of bridge/tide gates)	*Spartina alterniflora*	1.8 m (1)[c]		41°15′39″N 72°48′34″W
Hoadley-1 Hoadley-2 Hoadley-3	None	*Spartina alterniflora* *Spartina patens*	2.0 m (4)[c]		41°15′42″N 72°44′11″W
East-1 East-2	None	*Spartina patens* *Spartina alterniflora*	1.7 m (1)[c]	1.18 m (1)[d]	41°16′12″N 72°39′24″W
Restricted					
Sluice-1	Wooden tide gate installed in 1847, replaced with more effective top-hanging gate in 1950's, currently operated May-November; salt hay mowing currently occurs every summer	*Distichlis spicata* *Spartina patens* *Spartina alterniflora*	Winter: 1.4 m (3)[c] Summer: 0.70 m (3)[c]	0.89 m (1)[d]	41°16′20″N 72°40′00″W
Sluice-2	As above, plus culvert under Amtrak line	*Distichlis spicata* *Spartina patens* *Spartina alterniflora*	0.24 m (1)[c]	0.79 m (1)[d]	41°16′20″N 72°40′00″W
Leetes-1 Leetes-2	Wooden tide gate installed by early 1900's, replaced with more effective metal flap gate in 1952, currently operated May-November; salt hay mowing currently occurs every summer	*Distichlis spicata* *Salicornia europea* *Spartina patens*	0.31 m (2)[e]	0.48 m (2)[e]	41°15′39″N 72°42′54″W
Sybil-2 Sybil-3	Wooden tide gate installed under State Route 146 in early 1900's, replaced in 1939 after hurricane damage, operated year round primarily for flood control	*Phragmites australis* *Spartina patens*	0.38 m (2)[c,d]	0.37 m (1)[d]	41°15′39″N 72°48′34″W
Restored					
Branford-1 Branford-2	Two tide gates were allowed to fall into disrepair; they were removed and a bridge opening was widened in the mid-1970's	*Spartina alterniflora*	1.5 m (1)[c]	1.18 m (1)[d]	41°16′25″N 72°48′18″W

[a] Average tidal range for selected spring tides (number of tides measured is shown in parentheses).
[b] Absolute elevation (National Geodetic Vertical Datum) of water at high tide for selected spring tides (number of tides measured is shown in parentheses).
[c] Source: this study.
[d] Source: United States Army Corps of Engineers 1994b.
[e] Source: United States Army Corps of Engineers 1994a. Note: these measurements were made with the tide gate open for the winter, so that the only restriction to flow was the culvert.

deposition from weapons testing. Average accretion rates over the last ~100 years were derived from the best-fit lines of the profiles of ^{210}Pb against depth, using the constant initial concentration (CIC) model (Krishnaswami et al. 1971). Pb and Cs sedimentation rates were also calculated on a mass basis (g cm^{-2} yr^{-1}); we refer to these values as accumulation rates.

A subsample of each ground section was ashed at 480°C for 8 h to determine organic matter (OM; %) from loss on ignition (LOI). An additional subsample of each section was analyzed for C and N using a LECO CHN-8000, which carries out combustion at 950°C. C and N analyses were carried out in triplicate and repeated if the standard deviation was > 1% C or > 0.1% N. CHN analysis of 28 randomly selected ashed samples indicated that none of the cores had significant amounts of inorganic C. An excellent correlation ($r^2 = 0.96$) was found between C concentrations as measured by CHN analysis and OM contents as measured by LOI, which provides further evidence of the quality of our measurements and of the absence of inorganic C in these sediments. A C:OM ratio of 0.48 was found, which is within the range of conversion factors used by others (Morris and Whiting 1986; Craft et al. 1991).

LOI data were used, together with the Cs dating results, to calculate mass accumulation rates for organic (OM) and inorganic (IM) material. These rates were then converted to vertical OM and IM accretion rates by assuming a density of 1.1 g cm^{-3}

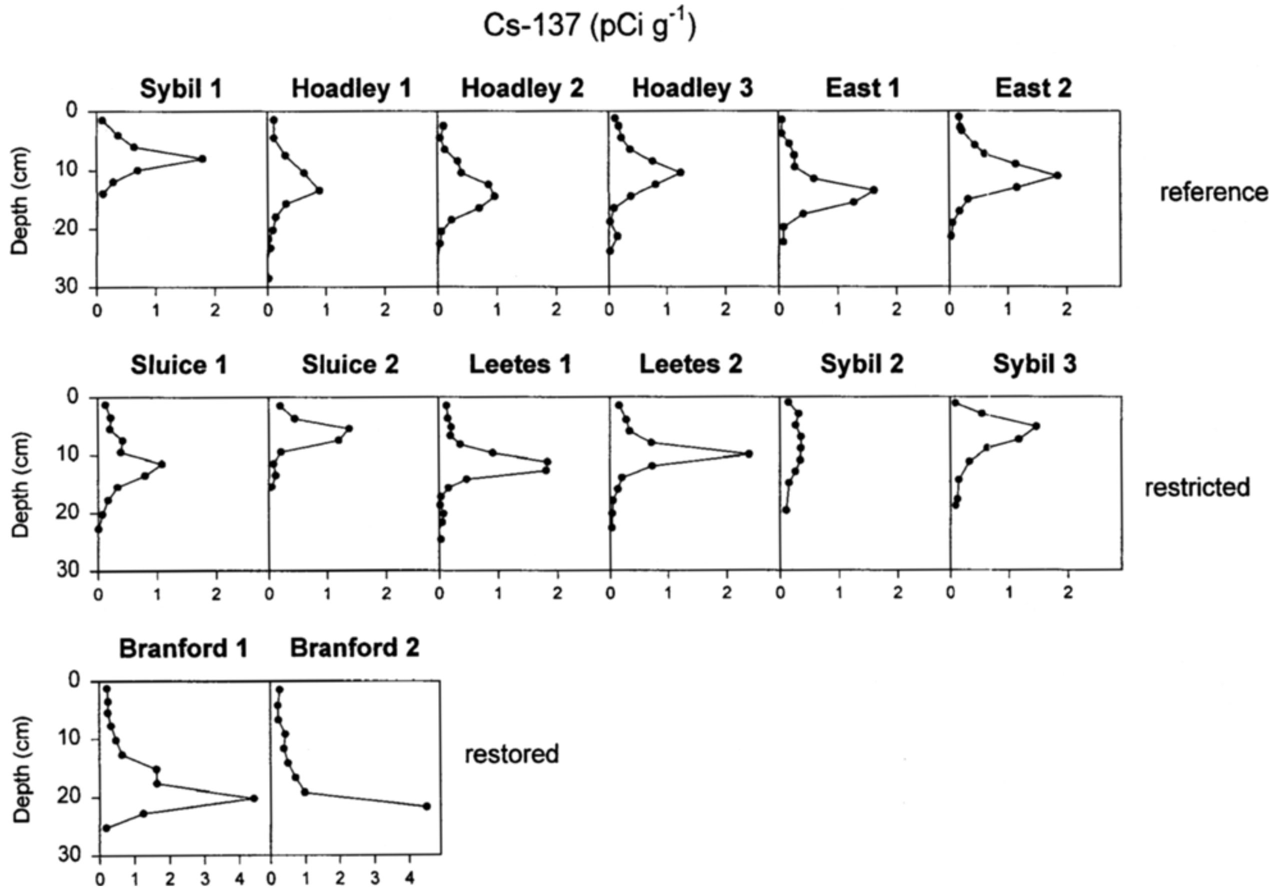

Fig. 2. ^{137}Cs activity (pCi g^{-1}) as a function of depth. Top row: reference marsh cores. Middle row: restricted marsh cores. Bottom row: restored marsh cores.

for OM and 2.6 g cm^{-3} for IM (Bricker-Urso et al. 1989); the remainder of the overall vertical accretion was ascribed to pore space.

Statistical analyses were carried out using SigmaStat (Fox et al. 1994). The 5% probability level was generally used to indicate significance, except as indicated in the text. Accretion and accumulation rates for the restored and restricted marsh cores were each compared to the corresponding reference marsh values using *t*-tests or the nonparametric equivalent. Bulk densities of 10-cm depth increments from the restricted and reference marsh cores were compared by *t*-test, as were the maximum bulk density in each core, the minimum carbon concentration in each core, and the average C:N ratio of each core.

Results and Discussion

Dating

The quality of the ^{137}Cs profiles (Fig. 2) was generally quite good, with all cores except Sybil-2 showing a distinct peak corresponding to the 1963 maximum in Cs release. Tau values, a measure of core resolution (Miller and Heit 1986), averaged 9.2 years. The ^{210}Pb profiles (Fig. 3) varied in quality, with 3 cores (East-2, Branford-1, Branford-2) showing large subsurface peaks in activity, peaks which may be due to large changes in sedimentation rate over time (Oldfield and Appleby 1984) or to post-depositional mobility of ^{210}Pb (Ridgway and Price 1987; Benoit and Hemond 1990; Urban et al. 1990; Benoit and Hemond 1991; Cundy and Croudace 1995). Several cores showed other deviations from exponential decay, including four cores (Sybil-1, East-1, Sluice-1, and Leetes-2) which had relatively flat activity profiles in the surface 5–10 cm; this may be a result of changes in sedimentation rate or of a surface mixed layer (though the ^{137}Cs profiles show no evidence of a mixed layer). Because of these difficulties with the ^{210}Pb profiles, we have focused primarily on interpretation of the ^{137}Cs data. For comparison purposes, we have derived average accretion rates over the last 100 years (using the constant initial concentration (CIC) model (Krishnaswami et al. 1971)) from the best-fit lines of the ^{210}Pb profiles (with exclusion of the

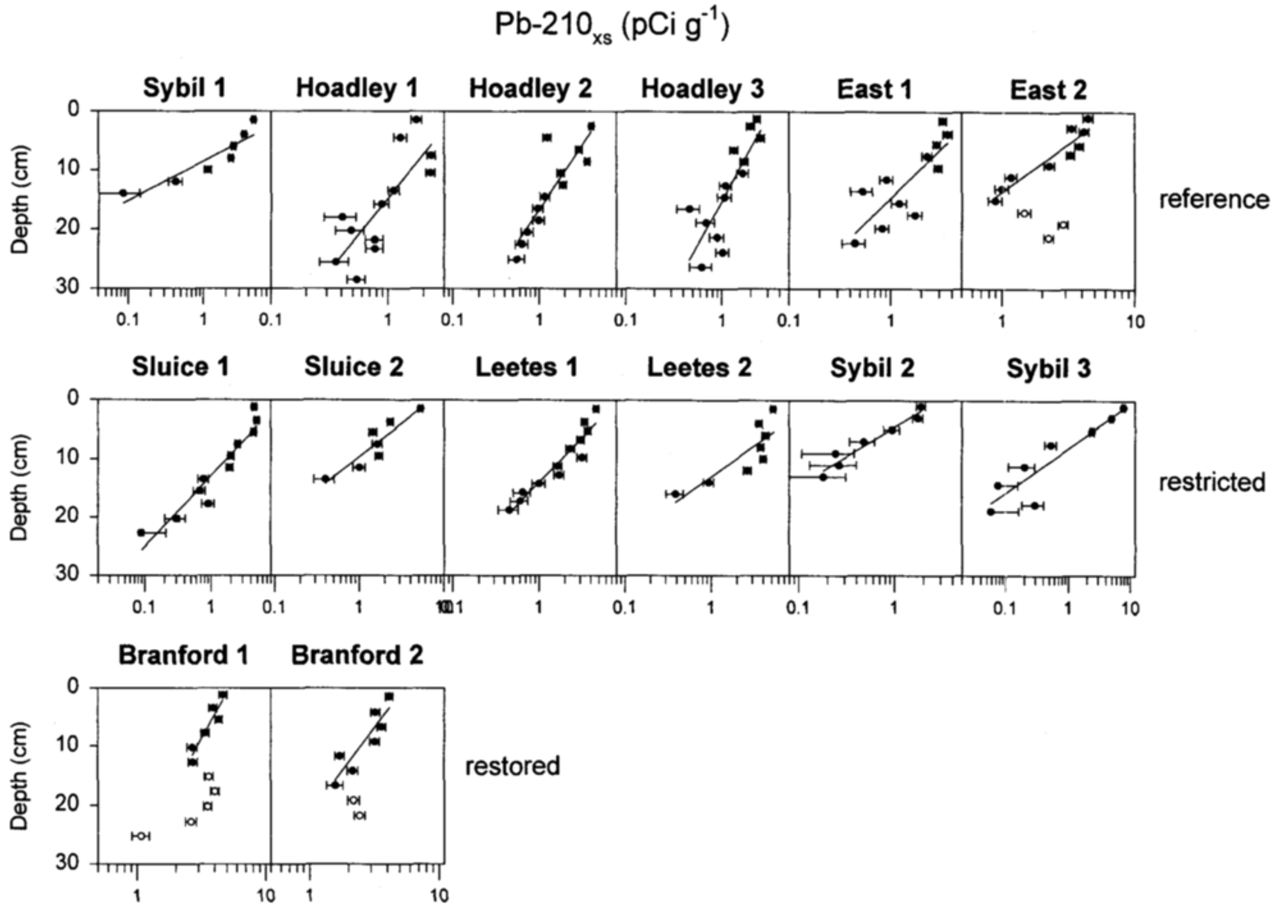

Fig. 3. Excess ^{210}Pb activity (pCi g^{-1}) as a function of depth. Top row: reference marsh cores. Middle row: restricted marsh cores. Bottom row: restored marsh cores. Error bars represent 1σ counting errors. Lines show best fit to the data, with the exclusion of subsurface activity peaks from East-2, Branford-1, and Branford-2 (open symbols).

subsurface peaks from three cores), with reasonably good r^2 overall (0.64 to 0.94 for the 14 cores). Application of the constant rate of supply (CRS) method (Oldfield and Appleby 1984) proved infeasible because several of the cores were not deep enough to provide complete ^{210}Pb inventories.

Vertical accretion rates for the reference marshes averaged 0.37 $\pm$ 0.03 cm yr^{-1} (mean $\pm$ standard error) using Cs dating, and 0.36 $\pm$ 0.07 cm yr^{-1} using Pb dating (Tables 2 and 3, Fig. 4a). These values are higher than the local rate of RSLR (0.16 cm yr^{-1} for the period 1963–1995; 0.17 cm yr^{-1} for 1939–1995; based on the New London, CT tide gauge), indicating that these marshes are more than keeping pace with sea level rise. Because of autocompaction at depth (Kearney et al. 1994), these recent sedimentation rates are an overestimate of long-term elevation change. The restricted marshes had slightly lower vertical accretion rates (average of 78% and 50% of reference marshes, by Cs and Pb dating, respectively), a difference which was not statistically significant at the 0.05 level (see Table 3). It should be pointed out that our sample size (number of cores) was too small to ascertain small differences in accretion rate, particularly given the large spatial variability in these values even within a given marsh (Kearney et al. 1994). The average difference we measured between restricted and reference marsh accretion rates (0.08 and 0.18 cm yr^{-1}, by Cs and Pb dating, respectively), if real, could result in a substantial difference in marsh surface elevation over periods of a century or more. Our results show that the restricted marshes currently have a positive accretion rate (i.e., they are not losing elevation), and that this rate is, at a minimum, within a factor of ~2 of accretion rates in healthy marshes. The higher accretion rates determined over the last 30 years (Cs dating), as compared to the rates over the last 100 years (Pb dating), may indicate that accretion rates in the restricted marshes have increased over this century as the marshes recovered from the initial installation of flow restrictions.

The restored marsh has responded to removal

TABLE 2. Sedimentation data for individual cores.

	Core Quality		Vertical Accretion Rate ($cm\ yr^{-1}$)					Mass Accumulation Rate ($g\ m^{-2}\ yr^{-1}$)				
	^{210}Pb r^{2a}	^{137}Cs τ (yr)[b]	^{210}Pb Total	^{137}Cs Total	^{137}Cs OM[c]	^{137}Cs IM[d]	^{137}Cs Pore Space	^{210}Pb Total	^{137}Cs Total	^{137}Cs OM[c]	^{137}Cs IM[d]	^{137}Cs N
Reference												
Sybil-1	0.84	9.2	0.11	0.25	0.027	0.006	0.22	170	450	290	160	6.1
Hoadley-1	0.64	8.8	0.52	0.42	0.033	0.029	0.36	1600	1100	360	750	8.4
Hoadley-2	0.77	7.9	0.38	0.42	0.036	0.029	0.36	1000	1200	400	760	7.8
Hoadley-3	0.68	11	0.59	0.33	0.023	0.024	0.28	1700	880	250	630	6.3
East-1	0.67	5.9	0.34	0.44	0.027	0.040	0.37	1200	1300	300	1000	8.1
East-2	0.88	9.9	0.24	0.34	0.039	0.030	0.28	820	1200	430	780	11
Restricted												
Sluice-1	0.90	9.8	0.18	0.38	0.022	0.047	0.31	1000	1500	240	1200	7.9
Sluice-2	0.83	11	0.19	0.19	0.015	0.018	0.15	810	640	170	470	5.4
Leetes-1	0.91	5.0	0.23	0.39	0.036	0.069	0.28	1400	2200	390	1800	13
Leetes-2	0.70	6.8	0.21	0.31	0.019	0.038	0.25	920	1200	210	1000	8.3
Sybil-1	0.94	19	0.14	0.25	0.012	0.041	0.20	800	1200	130	1100	5.2
Sybil-2	0.86	13	0.15	0.25	0.021	0.007	0.22	470	420	230	180	5.8
Restored												
Branford-1	0.87	6.5	0.61	0.63	0.034	0.029	0.56	1100	1100	380	760	11
Branford-2	0.81	4.3	0.49	0.69	0.034	0.043	0.61	1100	1500	380	1100	12

[a] r^2 value for best fit-line of ^{210}Pb activity against depth. Subsurface peaks were excluded from Sybil-2, Branford-1, and Branford-2.
[b] Resolution of Cs profile [Miller and Heit 1986].
[c] Organic matter.
[d] Inorganic matter.

of the flow restriction by accreting sediment much more quickly than reference marshes over the last 30 years (178% of reference value; $p < 0.05$; see Tables 2 and 3, Fig. 4a). This has enabled the marsh surface elevation to adjust to the higher water levels resulting from restoration.

Sources of Sediment for Marsh Accretion

When the Cs and Pb profiles were used to calculate mass accumulation rates rather than vertical accretion rates, both the restricted and the restored marshes appeared very similar to the reference marshes (Table 3 and Fig. 4b). Any differences which may have existed in vertical accretion rates (up to a factor of 2 or so) were apparently a result of differences in bulk density and not in sediment supply.

What, then, were the sources of sediment to these marshes? OM and IM mass accumulation rates, calculated from LOI data and Cs dating, are shown in Tables 2 and 3 and Fig. 4b. As can be seen in Fig. 4b, IM accounted for the majority of mass accumulation for all three types of marshes. There were large variations from core to core in rates of IM accumulation (Table 2), but no systematic differences related to flow regime. The restricted marshes did not appear to have a lower supply of IM, in contrast to results from other studies relating tidal flow to IM accumulation (Gosselink and Turner 1978; Craft et al. 1988; Craft et al. 1993; Cahoon and Reed 1995; Portnoy and Giblin 1997b). This may have been due to the seasonal operation of the tide gates in 2 of the 3 restricted marshes (Sluice and Leetes). During the months when the tide gates were open (November–May), these marshes were flooded with a frequency even greater than the reference marshes (because of their lower elevations), and thus presumably received an ample supply of sediment.

OM accumulation rates were significantly lower in the restricted marshes than in the reference marshes (Fig. 4b and Table 3). This may have been due to higher rates of decomposition as a result of the lower water table, or to removal of OM through salt hay mowing, which occurs at 2 of the 3 restricted marshes (Sluice and Leetes). The different mix of vegetation that dominates each marsh may also play a role.

When OM and IM accumulation rates were converted to vertical accretion rates (Fig. 4a), we found, as expected, that pore space dominated the vertical accretion in all the cores studied. Rates of both OM and pore space accretion were lower in the restricted marshes than in the reference marshes ($p = 0.044$ and $p = 0.055$, respectively; Table 3), suggesting that the reduced OM supply in the restricted marshes may contribute to lower porosity, through the effects of OM on sediment structure. Additional support for the effect of OM on sediment porosity comes from the strong negative correlation between OM content and bulk density (Fig. 5). The overriding importance of OM

TABLE 3. Average sedimentation rates for reference, restricted, and restored marshes (mean ± standard error). P values shown are probability that indicated parameter is not different from reference marsh (t-test, except where otherwise indicated; NS = not significant, $p > 0.10$).

	Vertical Accretion Rate (cm yr⁻¹)					Mass Accumulation Rate (g m⁻² yr⁻¹)				
	^{210}Pb Total	^{137}Cs Total	^{137}Cs OM[a]	^{137}Cs IM[b]	^{137}Cs Pore Space	^{210}Pb Total	^{137}Cs Total	^{137}Cs OM[a]	^{137}Cs IM[b]	^{137}Cs N
Reference	0.36 ± 0.07	0.37 ± 0.03	0.031 ± 0.003	0.026 ± 0.005	0.31 ± 0.03	1100 ± 200	1020 ± 130	340 ± 30	680 ± 120	8.0 ± 0.8
Restricted	0.18 ± 0.01 p = 0.065[c]	0.29 ± 0.03 NS	0.021 ± 0.003 p = 0.044	0.037 ± 0.009 NS	0.24 ± 0.02 p = 0.055	900 ± 120 NS	1200 ± 300 NS	230 ± 40 p = 0.043	1000 ± 200 NS	7.6 ± 1.2 NS
Restored	0.55 ± 0.06 NS	0.66 ± 0.03 p = 0.002	0.034 ± 0.000 NS	0.036 ± 0.007 NS	0.59 ± 0.02 p = 0.001	1125 ± 5 NS	1320 ± 180 NS	378 ± 0 NS	940 ± 180 NS	11.5 ± 0.6 p = 0.051

[a] Organic matter.
[b] Inorganic matter.
[c] Mann Whitney rank sum test.

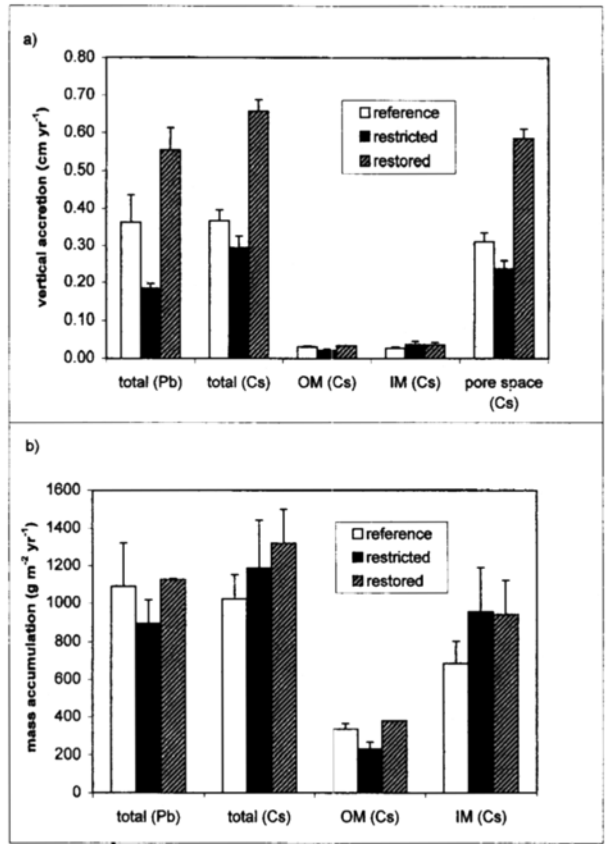

Fig. 4. Vertical accretion rates (a) and mass accumulation rates (b) in the reference ($n = 6$), restricted ($n = 6$), and restored ($n = 2$) marsh cores (mean ± SE). Rates are given as total accretion/accumulation based on ^{210}Pb and ^{137}Cs dating, and accretion/accumulation of individual components (OM = organic matter; IM = inorganic matter; and pore space) based on Cs dating only.

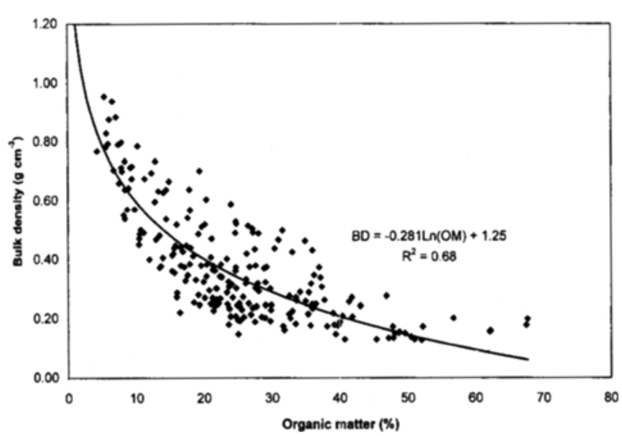

Fig. 5. Bulk density (g cm^{-3}) vs. organic matter content (%; by loss on ignition). Note the inverse correlation between the two.

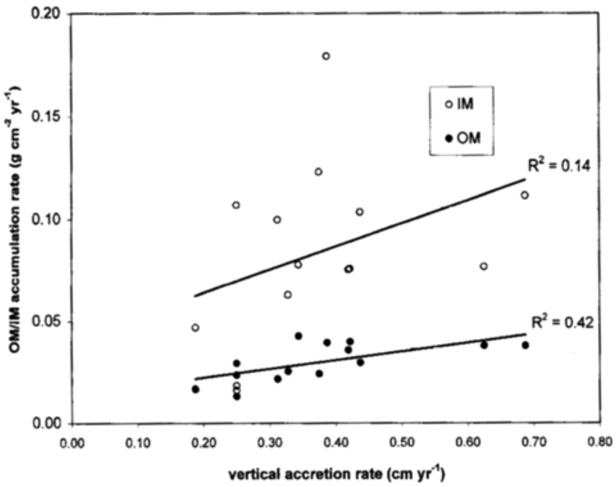

Fig. 6. Accumulation rate of organic matter (OM) and inorganic matter (IM) vs. overall accretion rate for each core. Note that OM accumulation is better-correlated with overall accretion than is IM accumulation.

in controlling the overall accretion rate has been suggested by others (Bricker-Urso et al. 1989; Callaway et al. 1997), and is confirmed by the fact that the correlation between OM accumulation and overall accretion for our cores is substantially stronger than the correlation between IM accumulation and overall accretion (Fig. 6).

The restored marsh, despite its much higher vertical accretion rate, did not differ from the reference marshes in either OM or IM supply (Fig. 4b). It was, rather, the higher porosity of these sediments that allowed these marshes to gain elevation so rapidly.

Bulk Density, C and N Content

The bulk densities of the cores from the reference and restored marshes were generally in the 0.2–0.4 g cm^{-3} range, and showed little variation with depth (Fig. 7). The restricted marsh cores, on the other hand, showed a marked increase in density with depth, and reached maximum densities which were significantly larger than the maximum

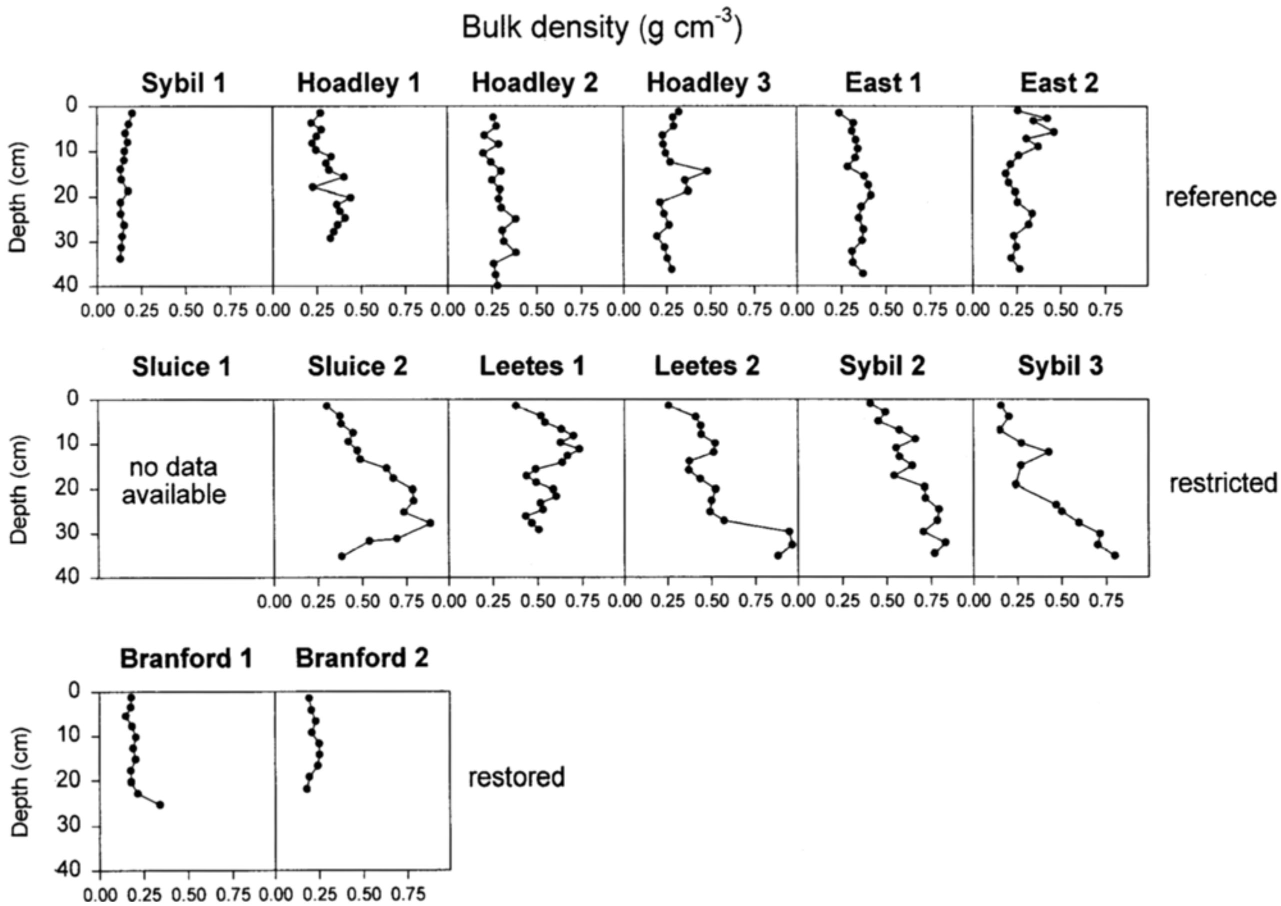

Fig. 7. Bulk density (g cm^{-3}) as a function of depth. Top row: reference marsh cores. Middle row: restricted marsh cores. Bottom row: restored marsh cores. Restricted marsh cores show high bulk densities at depth, while other cores show lower, more constant values.

TABLE 4. Average sediment parameters for reference, restricted, and restored marshes (mean ± SE). For each core, BD_{max}, C_{min}, and $C:N_{avg}$ are the maximum bulk density, the minimum C content, and the mean C:N atomic ratio. respectively. P values shown are probability that indicated restricted marsh value is not different from reference marsh (*t*-test).

	BD_{max} ($g\ cm^{-3}$)	C_{min} (%)	$C:N_{avg}$
Reference	0.40 ± 0.04 (n = 6)	11 ± 2 (n = 6)	22.0 ± 0.9 (n = 6)
Restricted	0.84 ± 0.03 (n = 5) $p < 0.0001$	2.6 ± 0.5 (n = 6) $p = 0.008$	15.8 ± 0.9 (n = 6) $p = 0.0005$

values seen in the reference marsh cores (Table 4). When bulk density was calculated for 10 cm depth increments for each core (0–10, 10–20, etc.), the restricted marshes were similar to the reference systems in the top 10 cm, but had significantly higher bulk densities below that depth (Fig. 8). This increase in bulk density with depth was accompanied by a decrease in C content (Fig. 9) to much lower minimum levels than in the reference marshes (Table 4). The only core which did not show the pattern of high bulk density and low C content at depth was Leetes-1, which was the shortest of the restricted marsh cores.

The high bulk densities and low C concentrations found at depth in the restricted marsh cores point to a period of increased compaction and organic matter decomposition in these marshes. This may correspond to the period following the initial installation of the flow restrictions and may reflect the response of the marshes to the lowered water table and the increased air entry into marsh sediments.

The N profiles generally showed the same patterns as the C profiles (data not shown). The N signal was damped relative to the C signal, with the overall range of N variation (8.5 times) being approximately half that of C (16 times). This can also be seen in the positive correlation between C and C:N ratio (Fig. 10), indicating that samples which were lowest in organic matter (low C) have the highest proportion of N in that organic matter (low C:N). This presumably reflects the well-known immobilization of N during the "decomposer" phase of OM decomposition, which causes a decrease in C:N ratio as decomposition proceeds (Marinucci 1982; Marinucci and Bartha 1982; Rice 1982; Valiela et al. 1985; Benner et al. 1991; White and Howes 1994a; White and Howes 1994b; White and Howes 1994c). As a result of this change in sediment C:N with C content, the sediments from the restricted marshes, with their lower C concentration, have a significantly lower average C:N ratio than the reference marsh sediments (Table 4).

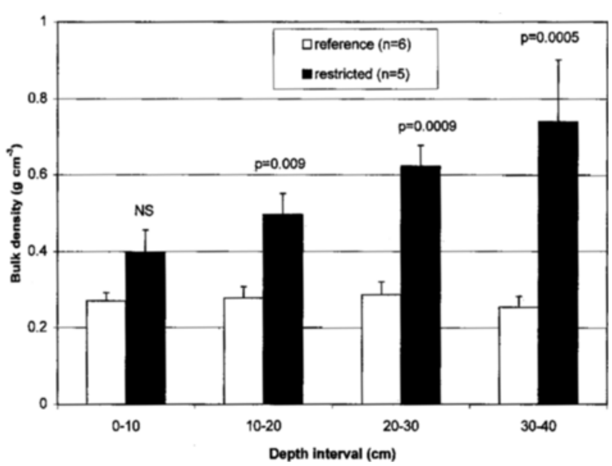

Fig. 8. Bulk density (mean ± SE) for 10 cm depth increments for the reference and restricted marsh sediment cores. P values shown are from *t*-test; NS = not significant.

Burial in marsh sediments is a semi-permanent sink for nitrogen, which is particularly important in salt marshes which border eutrophic, N-limited estuaries such as Long Island Sound (Wolfe et al. 1991; Long Island Sound Study 1994). We calculated N burial rates over the last 30 years using the Cs dating results. Despite the lower OM accretion rate found for the restricted marshes (see above), we found no difference in N burial between the restricted and reference marshes (Tables 2 and 3). This is a direct result of the lower C:N ratio in the restricted marshes, which leads to greater N immobilization per unit OM buried.

Restricted Marsh History—A Speculative Reconstruction

The C concentration data can be used, together with the Cs dating, to tentatively reconstruct the history of the restricted marshes (Fig. 9). We use the Cs peaks for this purpose, rather than the Pb dating, because of deviations from exponential decay which lead to uncertainties in interpretation of the Pb profiles (see above). We have identified up to 5 different periods in these cores:

1. Period I, seen only in the oldest core (Sluice-2), is a period of relatively high C concentrations, corresponding to the healthy salt marsh existing at this site before installation of the tide gate (pre 1850).
2. Period II, a period of lower C concentrations (and high BD's), reflects the initial installation of flow restrictions. We suggest that this was a

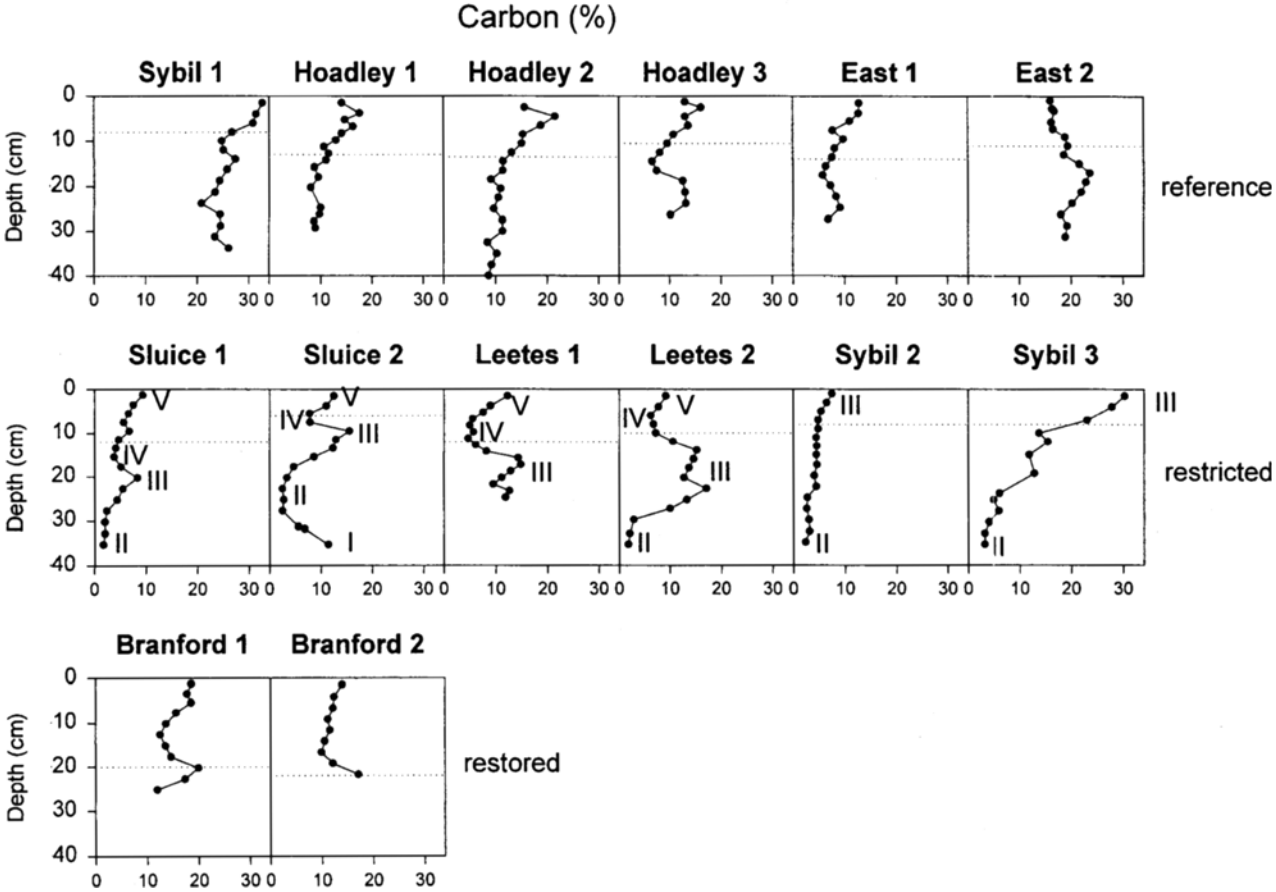

Fig. 9. Carbon content (%) as a function of depth. Top row: reference marsh cores. Middle row: restricted marsh cores. Bottom row: restored marsh cores. Dotted line represents the depth of the 1963 ^{137}Cs peak (see Fig. 2). For restricted marsh core numbering scheme, see "Restricted Marsh History—A Speculative Reconstruction," in text.

period of lowered water tables, rapid OM decomposition, and subsidence of the marsh surface. As discussed above, this period is seen in all but the shortest restricted core (Leetes-1).

3. Period III, a period of higher C concentrations (and lower BD's), represents the recovery of the marshes from the restriction to tidal flow. According to this model, the subsidence occurring in Period II led to a new, lower marsh surface which was again inundated more frequently, and which once again began to accumulate OM. In one of the marshes studied (Sybil), this period extends to the present, but in the other two restricted marshes, a new phase of tidal restriction led to two additional periods:
4. Period IV, a period of lower C concentrations, is a response to the more effective tide gates installed in the 1950's at both Sluice and Leetes. These flow restrictions led to a new period of lowered water tables, OM decomposition, and low accretion rates. Note that the 1963 Cs peak falls during this period, as expected.
5. Period V is again a period of recovery, in which C concentrations again increase (and BD's decrease) in response to more frequent inundation, as in Period III.

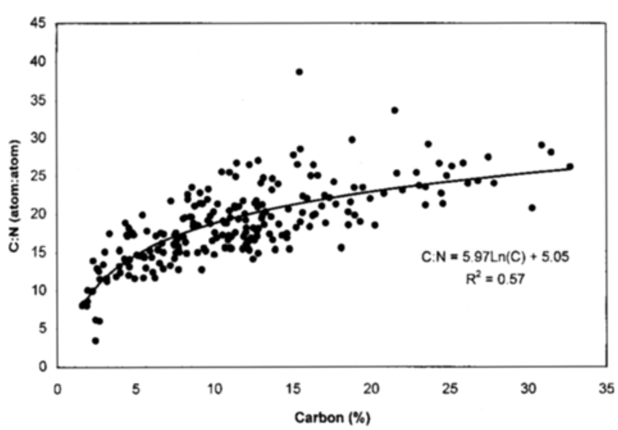

Fig. 10. Carbon-nitrogen atomic ratio versus carbon content (%). Note the positive correlation between the two parameters.

This reconstruction is clearly speculative, but fits nicely with the available historical information on flow restrictions at these sites, specifically the two phases of flow restriction at two of the three restricted sites. The broad outlines of this model—a period of acute trauma upon initiation of flow restriction, followed by a period of recovery—are supported by several pieces of evidence:

1. The restricted marsh sediments show very high bulk densities and low C contents at depth, followed by surface values more typical of healthy salt marsh sediments.
2. Recent sedimentation rates at these marshes are positive, while at the same time elevation measurements for at least one of these marshes (Leetes; United States Army Corps of Engineers 1994a) indicate an elevation loss of ~1m since tide gates were installed (see Frenkel and Morlan 1991; Thom 1992; Roman et al. 1995; Rozsa 1995b; Portnoy and Giblin 1997b for evidence of subsidence in other restricted marshes).

Restoration

There are increasing efforts in Connecticut and elsewhere to restore flow-restricted salt marshes by enhancing tidal inflow (Rozsa 1995b). However, given the subsidence that has occurred in many of these systems, restoration of full natural tidal flow would, in many cases, lead to drowning of the marsh and conversion to open water (e.g., Lost Lake, Guilford [Rozsa 1995b]). A partial restoration of flow is often sufficient to allow a substantial recovery of marsh structure and function (e.g., Barn Island Marsh [Sinicrope et al. 1990; Barrett and Niering 1993]; Drakes Island Marsh [Burdick et al. 1997]). In some cases, full tidal restoration can lead to faster marsh recovery (e.g., Mill Brook Marsh [Burdick et al. 1997]). Restoration of full flow is not often a viable option in southern New England, both because of engineering constraints (e.g., the size of the bridge opening) and because of the danger of flooding nearby structures. Even a partial flow restoration should be carefully modeled in order to determine that resulting water levels will not flood the marsh surface excessively (Roman et al. 1995). The goal of flow restoration should be an increase in water level (and salinity), but only within a range that will not overwhelm the capacity of the marsh to respond.

By these criteria, the restored marsh examined in this study is an example of a successful restoration. Abandonment of the tide gates resulted in higher water levels, which in turn caused high vertical accretion rates (see above), allowing the marsh surface to remain intertidal. The restoration was apparently also moderately successful in terms of vegetation change: the high marsh community present before removal of the tide gates has been replaced by a low marsh community dominated by *Spartina alterniflora* (United States Army Corps of Engineers 1994b). Two factors which may have contributed to the success of this restoration are the gradual nature of the increase in tidal flow (progressive loss of function of the tide gates over a several year period); and the fact that tidal restriction had not been severe enough to cause dominance of *Phragmites australis* before restoration. Even with these two mitigating factors, very high accretion rates were necessary in order for this marsh to remain an intertidal system. The high accretion rates of ~0.7 cm yr^{-1} measured in this marsh are probably an underestimate of the accretion rate since restoration, because the 33-year time period measured by the Cs dating technique includes approximately a decade of pre-restoration conditions. The actual accretion rate in this marsh over the last 20 years probably approaches the ~1 cm yr^{-1} observed in Louisiana marshes, which appears to be near the upper limit of marsh accretion rates.

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